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for Wind Installations with Novel Developments

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Definitions

Acronym	Description
Cat.	Category
CDF	Cumulative distribution function
CM	Condition monitoring
CTV	Crew transfer vessel
DBN	Dynamic Bayesian network
FEM	Finite element method
FM	Fracture mechanical
MTTF	Mean time to failure
O&M	Operation and maintenance
Pf	Probability of failure
PoD	Probability of detection
RBI	Risk-based inspection
RUL	Remaining useful life
SHM	Structural health monitoring
VoI	Value of information

Executive Summary

This deliverable presents a framework for risk-based optimal planning of O&M and inspections developed in LEANWIND WP4: “Operation and maintenance” in task 4.2: “Strategy optimization” in subtask T4.2.3: “Risk-based O&M”.

The framework concerns the problem of determining the optimal strategies for Operation & Maintenance (O&M) of deteriorating components in offshore wind turbines. Focus is on selecting optimal methods and times for inspections and repairs of selected components. The basis for the optimization include knowledge of the deterioration mechanics, knowledge of available inspection and condition monitoring methods, and knowledge of the costs associated with condition monitoring, inspections, repairs, and failures, including lost revenue due to downtime. The optimal strategy is defined as the strategy associated with lowest expected costs during the planned lifetime of the wind farm.

The central point in the risk-based approach is to capture the effect of maintenance on the failure rate, and the effect of condition monitoring and inspections on maintenance. To do so, probabilistic models are needed for deterioration, inspections, condition monitoring, and repairs. Using these models, the optimal decisions can in principle be found by solving a so-called Bayesian pre-posterior decision problem. However, direct optimization is not possible due to an exponential increase in computation time with the number of time steps.

Therefore, this framework uses decision rules for decisions on inspections and repairs, and thereby it becomes possible to find an optimal solution, among a set of candidate decision rules and variables. For this, a model has been developed for computation of the expected number of inspections, repairs, and failures for each set of decision rules and variables. Combining these with the costs of inspections, repairs, and failures, the expected lifetime O&M costs can be obtained for each set of decision rules and variables, and the optimal decision rules and variables can be identified. The computation of the expected number of inspections, repairs, and failures can be made using various methods.

The framework applies a method that rely on dynamic Bayesian networks. For simple decision rules, such as equidistant inspections, and repairs when a threshold for the inspection outcome is exceeded, the expected number of inspections, repairs and failures can be found directly from a Bayesian network, thus the computations are fast and lead to the exact result (given the input). For more complex decision rules, such as inspections whenever the probability of failure in the following time step reaches a threshold, simulations are needed for the computation of the expected number of inspections, repairs, and failures, and Bayesian networks can be used for estimating the probability of failure within the simulations. These computations are slow as they rely on simulations, and the accuracy of the results depends on the number of simulations.

The risk-based approach for optimal planning of O&M can be characterized as a predictive strategy for O&M planning where all information obtained in the remaining lifetime is considered by using decision rules. Decision rules are formulated for actions / maintenance in the future taking into account that the information is uncertain /

unknown at the time where the O&M strategy is selected. Bayesian decision theory provides the theoretical background.

This deliverable contains a case study, where the risk-based method is applied to the decision problem of wind turbine blade inspection and maintenance. For blade deterioration, typically the severity of deterioration is characterized by levels, e.g.: '1: cosmetic', '2: damage, below wear and tear', '3: damage, above wear and tear', '4: serious damage' and '5: critical damage'. A procedure based on the maximum likelihood method is developed for the estimation of transition probabilities in a Markov model. The input for the estimation is data from a database containing blade inspection data. The costs associated with repairs are assumed to depend on the defect size. For each defect size, an appropriate repair method has been identified, and the total repair costs including lost revenue are estimated using time series of wind and waves, as the lost revenue and rent of equipment depend on the time needed for the repair and the waiting time until the repair can be started.

Information about the blade health can be obtained using inspections and condition monitoring. Inspections can either be manned inspections performed using rope access or be unmanned inspections performed by drones. Drone inspections are assumed to be less effective in detecting damages compared to manned inspections, but are also cheaper. Condition monitoring is less reliable than the inspection techniques, but information can be obtained continuously without accessing the turbines, and the costs of condition monitoring is a one time expense. The reliability of the inspection and condition monitoring techniques are modelled using PoD (Probability of Detection) curves. Inspections are assumed to be mandatory before repairs, as repairs must be planned based on visual observations.

First, the optimal strategy was found, when no condition monitoring was available. The lowest costs were obtained using equidistant drone inspections every three months, and repairing damages of level 2 and above. The expected lifetime O&M costs per blade were 48.4 k€. Another promising strategy was to make drone inspections whenever the probability of failure of a blade exceeded a threshold. This strategy performed better than the strategy with equidistant inspections, when the inspection costs per blade was assumed constant. However, when considering the savings obtained by inspecting all three blades in a turbine simultaneously, the equidistant approach was superior. When condition monitoring was assumed to be available, the lowest costs were obtained using drone inspections whenever the probability of failure in the following month exceeded a threshold of $3 \cdot 10^{-7}$. The threshold approach performs better when condition monitoring is available, as the information from the condition monitoring system is used for estimation of the probability of failure. When condition monitoring was available, the expected lifetime O&M costs per blade were 34.8 k€. Thereby, the value of condition monitoring is 13.6 k€ per blade, or 40.8 k€ per wind turbine. Thus, it is beneficial to install a blade condition monitoring system, if the costs including installation and maintenance is less than approximately 40 k€.

The results presented above are based on the assumptions used in the case study in this deliverable. The framework presented in this deliverable can be used to obtain strategies for components whenever models for deterioration, inspections, condition monitoring, repairs and costs can be formulated.